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Revised spectral analyses of Galactic WC stars

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Abstract: A grid of models for Wolf-Rayet stars of the carbon sequence (WC) has been established with the Potsdam Wolf-Rayet (PoWR) model atmosphere code. In contrast to earlier versions, clumping and iron line blanketing are now taken into account. The spectra of more than 50 Galactic WC stars with subtypes ranging from WC4 to WC9 have been analyzed by finding the best-fitting model from the grid.

While the spectra of Wolf-Rayet stars of the nitrogen sequence (WN) can be nicely reproduced by a PoWR model fit, the WC spectra show a couple of features that cannot be consistently reproduced by a single model. Nevertheless, the models can be applied for their spectral analysis. The obtained parameters clearly reflect the sequence of WC spectral subtypes. From the positions of the WC stars in the Hertzsprung-Russell diagram we conclude that WC stars descend from stars with initial masses between 20 $M_\odot$ and 40 $M_\odot$ while stars with higher masses do not reach the WC stage.

1 Introduction

The Wolf-Rayet stars are divided into two main subtypes, depending on the dominance of nitrogen (WN) or carbon (WC) lines. The WC stars are evolved stars, with strong emission lines from helium, carbon and oxygen, that lost their outer hydrogen layers. However, their basic parameters are still uncertain and very different temperatures and mass-loss rates have been obtained in earlier analyses, such as Koesterke & Hamann (1995), Hamann, Gräfener & Koesterke (2003) or Gräfener & Hamann (2005). Spectral analyses of these stars require detailed modeling of their expanding atmospheres. The Potsdam Wolf-Rayet (PoWR) code can handle the non-LTE radiative transfer and account for the complex atoms required to reproduce the situation in the stellar atmosphere. Following the efforts of Barniske, Hamann & Gräfener (2006) we established a model grid to perform a coarse analysis of over 50 Galactic WC single stars ranging from the "early" subtype WC4 to the "late" WC9. In addition a few WN/WC transit type stars, the two WO stars WR 102 and WR 142 and six WC binaries have been analyzed.

2 Model Grid

In order to analyze a larger number of stars, a model grid has been established with the PoWR code, taking microclumping and iron line blanketing into account. The grid parameters are the stellar temperature T_* and the so-called "transformed radius"

$$R_\mathrm{t} = R_* \left[\frac{v_\infty}{2500\,\mathrm{km/s}} \middle/ \frac{\dot{M}\sqrt{D}}{10^{-4}\mathrm{M}_\odot/\mathrm{yr}} \right]^{\frac{2}{3}} . \tag{1}$$

Luminosity, clumping factor and terminal wind velocity as well as the chemical composition have been kept fixed over the whole grid, using $\log L/L_\odot = 5.3$, $D = 4$, $v_\infty = 2000\,\mathrm{km/s}$ and mass fractions of 55% Helium, 40% Carbon and 5% Oxygen. For iron group elements we set the mass fraction to 0.16%. Additional models with different abundances and with different velocities have been calculated for comparison and for reproducing the WC9 and WO spectra. The WC9 stars require models with lower terminal wind velocities ($v_\infty = 1000$-$1600\,\mathrm{km/s}$) than the earlier subtypes.

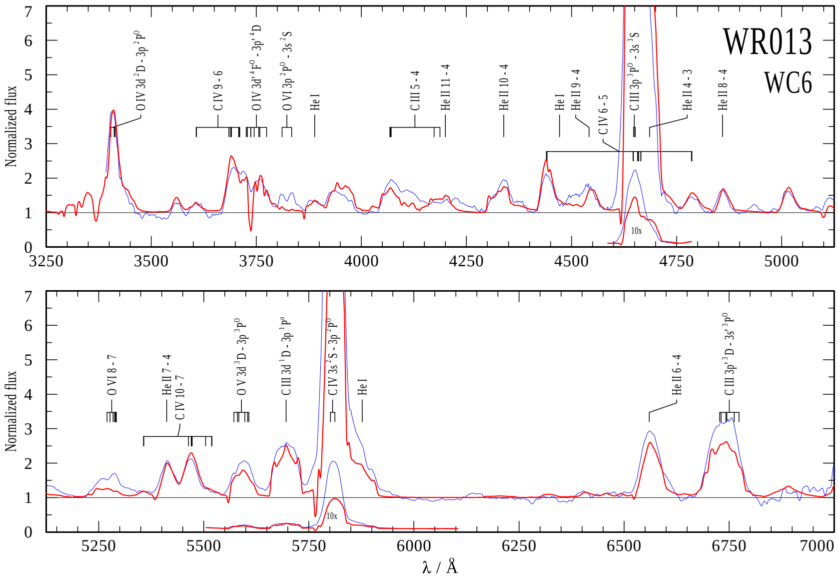

Figure 1: Optical spectrum of the WC6 representative WR 13 (blue) compared to the best-fitting PoWR model (red). The model reproduces most of the spectral features but underestimates the peak height of the prominent C IV line at 5808 Å. The same model fits to most of the Galactic WC6 single stars, although some of the peak heights do not match.

As an example of the fitting results, Fig. 1 shows the best fitting model for WR 13 compared to the observed spectrum by Torres & Massey (1987). The model reproduces most of the spectral features, although it tends to underestimate the peak heights of the most prominent lines. The good fit of the diagnostic line pair He II 5412 Å and C IV 5470 Å verifies the carbon-to-helium mass ratio of 40:55 as adopted for the model grid. There seems to be no difference in the chemical composition between the subtypes.

The locations of the analyzed Galactic WC stars in the $\log R_\mathrm{t}$-$\log T_*$-plane are shown in Fig. 2. In contrast to the WN stars, the WC stars form a one-dimensional sequence. From the subtypes WC8 to WC4, the stars align along a linear relation $\log R_\mathrm{t} \propto -2\,\log T_*$, while only the WC9 stars are lying apart. For the model grid with fixed L, v_∞ and D, this linear relation implies that the mass-loss rate is the same, as can be seen from combining Eq. (1) with $L \propto R_*^2\,T_*^4$.

The actual luminosities of the individual stars are obtained by scaling the spectral energy distribution of the grid models to photometric observations, which requires an independently known distance (cf. Sect. 3). With these individual luminosities, the constant mass loss from the linear relation in the model grid (Fig. 2) turns into the mass loss-luminosity relation

$$\dot{M} \propto L^{\frac{3}{4}} \tag{2}$$

provided that one adopts the same v_∞ and D for all stars. The empirical mass-loss rates of our sample range between $10^{-4.5}$ and 10^{-5} $M_\odot$/yr.

All stars located above the sequence in Fig. 2 are known to be binaries. Due to the neglection of the composite nature of their spectrum, they appear as stars with lower mass-loss rates and slightly lower temperatures. It turns out that the so-called "diluted emission line" (d.e.l.) criterion works indeed as a binary tracer for WC stars. A WC-s and WC-w classification as introduced by Koesterke & Hamann (1995) is not necessary.

The two WO2 stars WR 102 and WR 142 do not align with the rest of the sequence but require completely different models with 30% oxygen and a temperature of $T_* = 200$ kK to reproduce the prominent oxygen lines. Their extremely broad lines require a wind velocity of $v_\infty = 5000$ km/s.

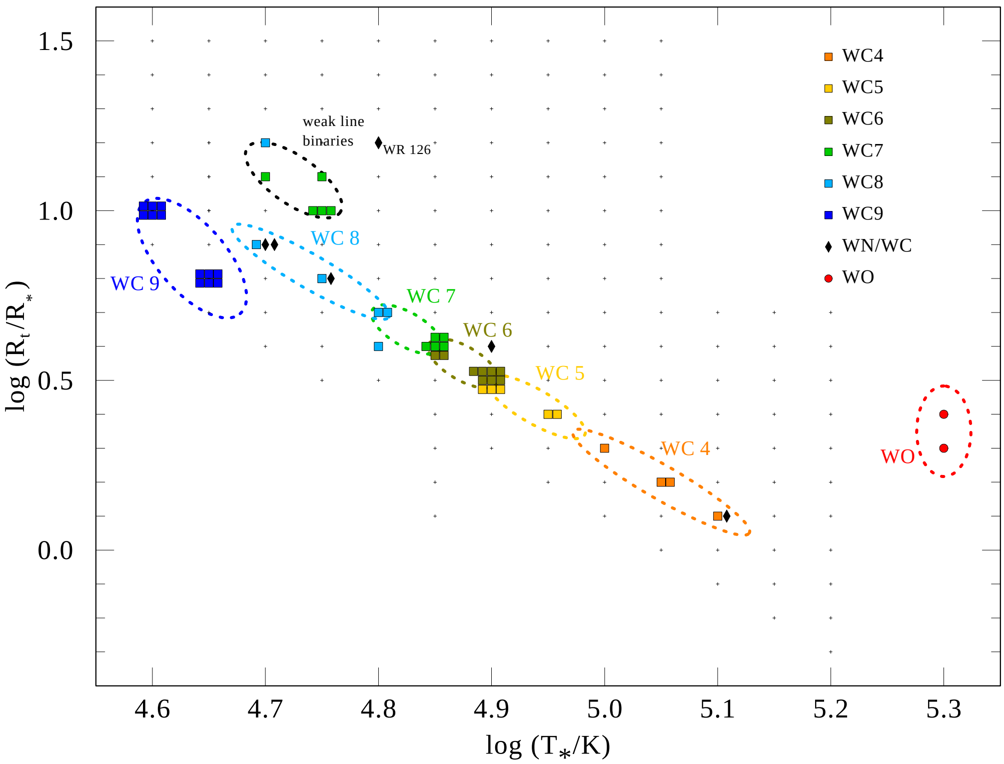

Figure 2: Location of the analyzed Galactic WC stars (colored symbols) in the $\log R_t$-$\log T_*$-plane. The subtypes form a one-dimensional sequence from the cooler WC9 to the hotter WC4 subtypes with a slight offset for the WC9 stars. The stars above the sequence turn out all to be binaries where the neglection of the composite nature of their spectra leads to an underestimate of their mass-loss rates.

A few stars show a spectral appearance in between the WN and WC type, termed WN/WC. Their spectral appearance and chemical composition is similar to the hydrogen-free WN stars, but with enhanced traces of carbon. We calculated small model grids with carbon abundances of 0.1% and 5%, keeping nitrogen at 1.5% and iron group elements at 0.16% mass fraction with the rest being left for helium. The positions in the $\log R_t$-$\log T_*$-plane for the WN/WC stars show that they are close to the WC sequence, with the exception of WR 126, which stands completely apart. However, the spectrum of WR 126 resembles a WC rather than a WN spectrum and is therefore classified as WC/WN (van der Hucht 2001).

The WN/WC stars may represent the standard evolutionary transition phase from the WNE to the WC stage. Alternatively, the enhanced carbon fraction in the WN/WC stars might come from dragged up material in some WNE stars having a special mixing process.

3 HR diagram and evolutionary models

To obtain the positions of the WC stars in the Hertzsprung-Russell diagram, luminosities have been determined by fitting the spectral energy distribution using flux-calibrated spectra and additional photometric observations from 2MASS. The stellar temperature T_* is given by the best fitting model. Of course the luminosity values also depend on the adopted stellar distance. Only some of the Galactic WC stars can be assigned to clusters or OB associations, from which we can infer the distance. For the other ones we adopt a subtype-magnitude calibration, assuming that all stars of the same WC subtype have more or less the same absolute magnitude. As this might not be close to reality, these stars are represented by smaller symbols, while those with known distances and therefore more trustworthy luminosities are represented by larger symbols in the HRD (Fig. 3).

With luminosity and temperature being determined we can obtain the position of the Galactic WC stars in the HR diagram and compare our results with evolutionary models. It turns out that the luminosities of the WC stars are mostly between $\log L/L_\odot = 4.8$ and $\log L/L_\odot = 5.5$, much lower than expected. Fig. 3 shows the evolutionary tracks with rotation by Meynet & Maeder (2003) compared to the obtained positions. Evolutionary models without rotation would lead to even more luminous tracks, enhancing the discrepancy between models and observations. In any case, most of the obtained luminosities are much lower than predicted by the tracks. Only the two WO stars seem to fit with the tracks, although they appear a bit more compact than predicted by the SN endpoint.

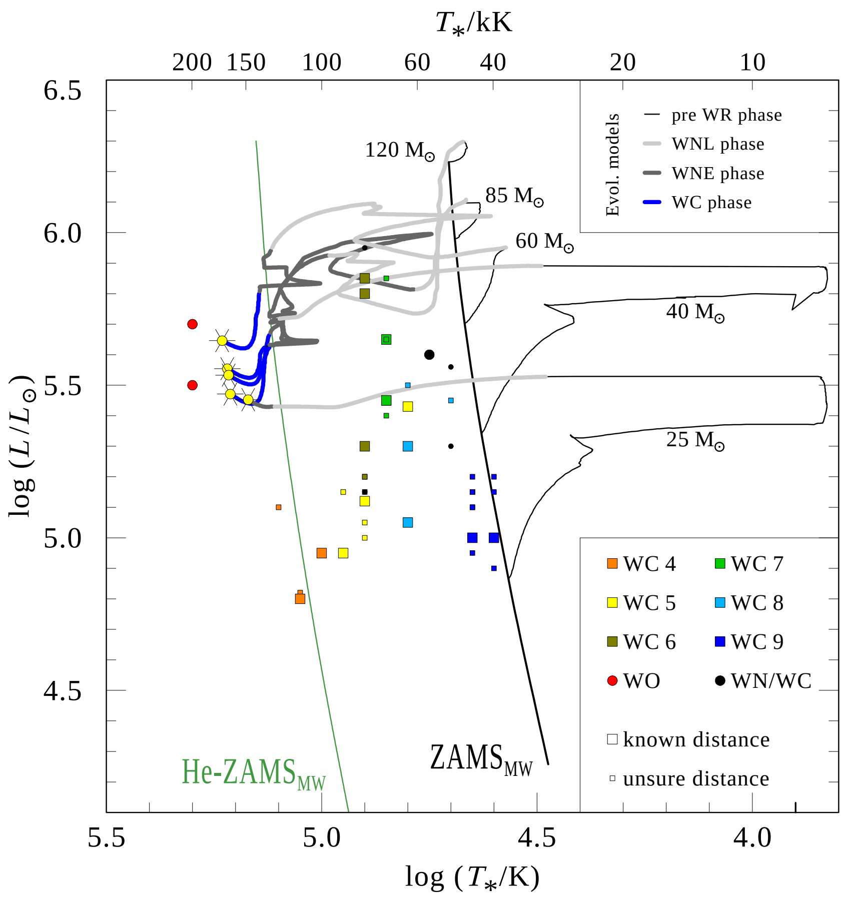

Figure 3: Hertzsprung-Russell diagram with the analyzed Galactic WC stars compared to the evolutionary tracks with rotation by Meynet & Maeder (2003). The part of the tracks which corresponds to the WC phase are drawn as thick blue lines, short prior to the SN explosion. The observed WC stars are less luminous and cooler than expected.

Interestingly the obtained WC positions in the HR diagram are close to the WNE positions (Hamann, Gräfener & Liermann, 2006), with the WNE luminosities being slightly higher than the WC values. The stellar temperatures T_* for the subtypes WC5 to WC9 are lower than the He-ZAMS where we would expect to find these helium burning stars without hydrogen. This can be explained with a stellar photosphere that is more extended than the hydrostatic stellar core. Only for WC4 and WO stars the stellar wind seems to be footed close to the core. Note that we plot the evolutionary models in Fig. 3 with respect to the effective temperature $T_{\rm eff}$ which refers to the radius of the hydrostatic core, without any correction for an extended stellar atmosphere.

The HRD positions question the scenario that WC stars evolve only or mostly from very massive progenitors. Instead it seems likely that these high-mass stars do not enter the WNE and WC stage after their WNL phase, but explode directly as supernovae. The WNE and WC stars instead evolve from lower initial masses in a post-RSG scenario. Vanbeveren et al. (1998) showed that higher mass-loss rates during the RSG branch can strip off the outer hydrogen layers, so that stars with an initial mass of $15\,M_\odot$ can make it to the WR stage. To enter the WC stage an initial mass of around $25\,M_\odot$ is required, sticking to the scenario from Vanbeveren et al. (1998). The luminosities for their tracks are lower than the ones from Meynet & Maeder (2003), leading to a better agreement with the obtained values.

4 Conclusions

The Galactic WC stars form a one-dimensional sequence in the $\log R_{\rm t}$-$\log T_*$-plane implying $\dot{M} \propto L^{3/4}$. They are less luminous and cooler than predicted by evolutionary models. The low effective temperatures might be explained by an extended layer under the photosphere. We find most WC stars at $\log L_{\rm WC}/L_\odot \leq 5.5$ and none above $\log L_{\rm WC}/L_\odot > 5.9$. The low observed luminosities contradict the common paradigm that WC stars evolve only from very massive stars. Instead our results indicate that WC stars descend only from stars with a medium-high initial mass between 20 $M_\odot$ and 40 $M_\odot$. Stars with higher initial masses might not be able to get completely rid of their hydrogen layers and explode already during their hydrogen-rich WNL or LBV phase.

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